ANL-ART-110 Rev. 1

Implementation of Software QA for SAS4A/SASSYS-1

Nuclear Engineering Division

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Abstract

In an effort to support closure of gaps in advanced reactor licensing pathways, a multi-year task to systematically develop sodium-cooled fast reactor (SFR) codes and methods for use in a licensing framework was launched as part of the DOE-NE Advanced Reactor Technologies (ART) Program's Regulatory Technology Development Plan (RTDP). This report documents Phase 2 of this task, which was focused on the finalization and initial implementation of a software quality assurance (SQA) program for SAS4A/SASSYS-1 and completion of high-priority SQA-related technical activities. The ultimate goal of this ongoing RTDP task is to develop an SQA framework that satisfies the fundamental requirements of relevant SQA standards and guidance while still maintaining sufficient flexibility and efficiency such that the framework can be sustained with modest resources.

The provisional SAS4A/SASSYS-1 SQA Program has undergone a trial application period during which numerous code development activities were completed and version 5.2 of the code was released in accordance with Program procedures. As a result of lessons learned during the trial application, SQA Program documentation has been revised to improve clarity and consistency. In addition to revision of Program documentation, several key quality-enhancing technical activities were also completed, including addition of 117 new V&V Test Suite cases, reconstruction of historical validation test cases based on TREAT experiments, improvement in coverage of the regression test suite, development of unit testing capabilities, and modernization of the Code Manual.

Despite the improvements to the SAS4A/SASSYS-1 SQA Program, several gaps still remain. These gaps are primarily related to engagement with the NRC, DOE, and industry regarding the acceptability of the SAS4A/SASSYS-1 SQA Program and code pedigree as it relates to the use of the code as a safety analysis tool. Resolution of these gaps requires sustained, direct engagement with these groups regarding the acceptability of design, requirement, and testing documentation for critical characteristics relevant to reactor designs anticipated to enter the licensing phase in the near term. Early engagement with these groups can help to reduce licensing obstacles for advanced reactors as a path toward SAS4A/SASSYS-1 acceptance is identified.

It should be noted that the SQA Program itself, including the Program plans, procedures, configuration management, and testing strategies, is considered to be at a fairly mature stage at the conclusion of this task. It is anticipated that the only revisions to the Program that may be required would be related to alignment with specific standards or requirements (e.g. NQA-1, DOE O 414.1D, etc.) as per feedback from the licensee or regulator. In this case, interaction with these groups is again required to determine if any Program revisions are required.

Beyond the gaps described above, the most significant challenge the SQA Program currently faces is sustainability within DOE annual funding constraints. Funding resources are needed to support the completion of SQA-related activities such as ticket reviews, documentation creation, development of expertise in SQA-related activities for developers (one-time training is insufficient), and regular Program surveillance, assessments, and audits.

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Acronyms

ART	Advanced Reactor Technologies
CGD	Commercial-grade Dedication
CM	Configuration Management
CMP	Configuration Management Plan
DOE	Department of Energy
IAPs	Implementation Action Plans
NRC	Nuclear Regulatory Commission
RTDP	Regulatory Technology Development Plan
SDD	Software Design Description
SFR	Sodium-cooled Fast Reactor
SQA	Software Quality Assurance
SQAP	Software Quality Assurance Plan
SRS	Software Requirements Specification
STP	Software Test Plan

1 Introduction

Deployment of a sodium fast reactor (SFR), whether as a test or demonstration facility in the research and development (R&D) space or as a commercial plant supported by the U.S. nuclear industry, requires a clear path forward to completion of a license application. Approval of a license application by the U.S. Nuclear Regulatory Commission (NRC) is contingent on, among other things, satisfactory demonstration of the design basis and response to transient and accident scenarios using accepted codes and methods. Similar analyses using accepted tools are also required for facilities authorized to operate by the U.S. Department of Energy (DOE).

In an effort to support closure of gaps in advanced reactor licensing pathways [1], a multi-year task (Figure 1.1) to systematically develop SFR codes and methods for use in a licensing framework was launched as part of the DOE-NE Advanced Reactor Technologies (ART) Program's Regulatory Technology Development Plan (RTDP) [2]. This report documents Phase 2 of this task, which was focused on the finalization and implementation of a software quality assurance (SQA) program for SAS4A/SASSYS-1, and specifically the adoption of Program procedures and initial implementation of regular QA surveillance. This report also discusses the completion of Phase 2 SQA-related technical activities, including improvements to qualification testing and code documentation. The ultimate goal of this ongoing RTDP task is to develop an SQA framework that satisfies the fundamental requirements of relevant SQA standards and guidance [3] while still maintaining sufficient flexibility and efficiency such that the framework can be sustained with modest resources.

An overview of the structure of this project is provided in Section 1.1. The remainder of Section 1 provides background information on the SAS4A/SASSYS-1 code (Section 1.2), summarizes key activities completed in Phase 1 (Section 1.3), and outlines the structure of the remainder of this report (Section 1.4).

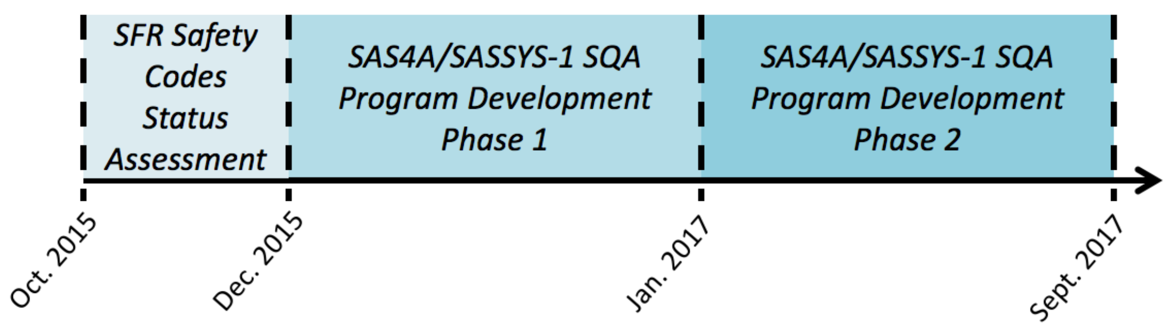

Figure 1.1: Timeline of SAS4A/SASSYS-1 SQA Program Development Phases

1.1 Project Background

During the initial assessment stage of the SQA effort between October and December of 2015 (see Figure 1.1), Argonne identified the safety analysis codes and methods required to support an SFR license application and summarized the state of each code [4]. A parallel effort by Oak Ridge National Laboratory (ORNL) [5] identified the SQA requirements necessary to develop and maintain a code of a pedigree acceptable for use in a domestic license application.

This work continued through January 2017 with Phase 1 (Figure 1.1). The efforts completed in Phase 1 [3] were focused on the initial development of a provisional SQA program for SAS4A/SASSYS-1 are summarized in Section 1.3. The Argonne-developed severe accident systems-level analysis code SAS4A/SASSYS-1 [6] was selected for this effort due to its prevalent use in a wide range of steady state and transient safety analyses, making it a key tool for use in a license application. Because of the code's expansive capabilities, SAS4A/SASSYS-1 is utilized by a large number of domestic and international universities, industry members, and regulating bodies for various applications, making it a highly relevant tool to the advanced reactor community. Further details on the impact and relevance of SAS4A/SASSYS-1 can be found in Section 1.2. Additionally, the SAS4A/SASSYS-1 development team is currently utilizing the majority of SQA best practices (e.g. configuration management, regression testing, etc.), making it an ideal candidate for efficient development of an SQA program under the RTDP effort.

As a continuation of the RTDP task, Phase 2 of Figure 1.1 entails the finalization and full implementation of the SAS4A/SASSYS-1 SQA Program. Completion of high-priority technical activities supporting the Program is also included in this phase. This report describes the progress completed in Phase 2, which is the last task to be sponsored by the RTDP.

1.2 SAS4A/SASSYS-1

This section provides background information on the SAS4A/SASSYS-1 code, including a summary of active users (Section 1.2.1) and a review of the capabilities of the code and its expected role in licensing (Section 1.2.2).

1.2.1 Users

SAS4A/SASSYS-1 is utilized by a number of groups in R&D and academia, both internationally and domestically. Active programs and collaborators that currently use SAS4A/SASSYS-1 include the following:

- **U.S. NRC:** The domestic regulator has licensed SAS4A/SASSYS-1 to evaluate its use for advanced non-light water reactor (LWR) license applications, particularly for liquid metal cooled reactors.
- **EBR-II IAEA Benchmark:** The DOE-NE Advanced Reactor Concepts program is supporting a high-profile Coordinated Research Project with the International Atomic Energy Agency based on the Shutdown Heat Removal Tests conducted at EBR-II. Both protected (SHRT-17) and unprotected (SHRT-45R) loss of flow tests are part of the benchmark activity. SAS4A/SASSYS-1 models of both tests have been developed to provide results under the CRP.
- **FFTF Benchmark:** Pacific Northwest National Laboratory (PNNL) and Argonne National Laboratory are preparing benchmark specifications for the Passive Safety Tests carried out at the Fast Flux Test Facility between 1984 and 1986. The most prominent tests were the loss of flow without scram. In collaboration with PNNL, Argonne National Laboratory is assessing the benchmark specifications and preparing SAS4A/SASSYS-1 models for verification and validation purposes.
- **GAIN Voucher Program:** Oklo, Inc. is one of the recipients of a Gateway for Accelerated Innovation in Nuclear award. Under the award, Oklo is gaining access to

knowledge of metallic alloy fuel. They are also investigating the available tools for fast reactor analysis and have acquired a license for Mini SAS.

- **NEUP Projects:** Several Nuclear Energy University Program awards are utilizing SAS4A/SASSYS-1 or Mini SAS as part of their scope of work. The University of California at Berkeley is using Mini SAS to evaluate safety benefits that might be achieved with autonomous reactivity control devices. Kansas State University and the University of Wisconsin are preparing experiments that can improve the modeling of thermal stratification in SFRs, with the goal that the improved models developed by their partners, The University of Illinois and Virginia Commonwealth University, respectively, would be incorporated into SAS4A/SASSYS-1.
- **GEH:** GE-Hitachi Nuclear Energy Americas, LLC has licensed Mini SAS to support pre-application license evaluations of the Advanced Reactor Concepts ARC-100 design and interactions with the Canadian Nuclear Safety Commission.
- **WEC:** Westinghouse Electric Company has licensed Mini SAS to support safety analysis for their lead-cooled fast reactor conceptual design and has initiated the process for acquiring a full license for SAS4A/SASSYS-1.
- **TerraPower TWR Reactor Concept:** TerraPower, LLC has licensed the SAS4A/SASSYS-1 source code to perform safety analysis studies for their Traveling Wave Reactor concept. TerraPower also funds code development activities that improve the modeling capabilities of SAS4A/SASSYS-1.
- **CEA Bilateral Collaboration:** An implementation agreement has been established between the U.S. DOE and the Commissariat à l'énergie atomique et aux énergies alternatives of France for cooperation in low carbon energy technologies. One purpose of the agreement is to evaluate the safety performance of the ASTRID reactor design. DOE uses the SAS4A/SASSYS-1 safety analysis code for simulations performed under the agreement.
- **CIAE Bilateral Collaboration:** The DOE-NE Office of International Nuclear Energy Policy and Cooperation has established the U.S.-China Bilateral Civil Nuclear Energy Cooperative Action Plan with the China Institute of Atomic Energy. Joint activities under the action plan include model development and safety analyses of the China Experimental Fast Reactor using SAS4A/SASSYS-1.
- **KAERI PG-SFR:** The Korean Atomic Energy Research Institute acquired a license for SAS4A/SASSYS-1 to perform safety analysis and model development for the Prototype Generation-IV Sodium Fast Reactor. KAERI is supporting metallic fuel severe accident model developments that will be incorporated into a future version of SAS4A/SASSYS-1.
- **KINS:** The Korea Institute of Nuclear Safety is an independent regulatory expert organization that supports the Nuclear Safety and Security Commission in Korea. KINS recently acquired a license for SAS4A/SASSYS-1 to support the regulatory obligations over the PG-SFR project.
- **KTH ELECTRA LFR Concept:** The Royal Institute of Technology (Kungliga Tekniska Högskolan) in Stockholm Sweden has a license for SAS4A/SASSYS-1 to perform natural

circulation design performance studies of their ELECTRA lead-cooled fast reactor concept.

- **JAEA Bilateral Collaboration:** The Civil Nuclear Energy Research and Development Working Group (CNWG) was established by the U.S.-Japan Bilateral Commission on Civil Nuclear Cooperation in 2012 to enhance coordination of joint civil nuclear research and development efforts. The Japan Atomic Energy Agency and Argonne National Laboratory plan to collaborate under the CNWG to improve the oxide fuel severe accident modeling capabilities in SAS4A/SASSYS-1.
- **NRA:** The Nuclear Regulatory Authority of Japan has acquired a license for SAS4A/SASSYS-1. The NRA plans to use SAS4A/SASSYS-1 to support SFR licensing evaluations in Japan.
- **CITON:** The Center of Technology and Engineering for Nuclear Projects (CITON) in Romania has a license for Mini SAS to perform analysis for the Falcon consortium to support the ALFRED (LFR) demonstration project.

1.2.2 Capabilities and Expected Role in Licensing

As an integrated systems analysis tool, SAS4A/SASSYS-1 possesses the capability to model the majority of steady state and transient phenomena expected to occur in an SFR. The initial FY16 effort [4] identified high level functional areas that characterize the behavior of a nuclear power plant. Table 1.1 lists the functional areas that must be analyzed in a license application and identifies the areas for which SAS4A/SASSYS-1 has some level of capability. Additional details on each functional area with regard to the specific behavior or phenomena can be found in [4]. Details on the maturity of the various models in SAS4A/SASSYS-1 can be found in [1]. As indicated by Table 1.1, SAS4A/SASSYS-1 treats, or provides supporting calculations to, nearly all functional areas. As no other systems analysis tool exists with such a wide range of capabilities and maturity, it is expected that SAS4A/SASSYS-1 will be utilized as a primary tool in safety analyses supporting a license application.

Table 1.1: SAS4A/SASSYS-1 Capability Description

Functional Area	SAS4A/SASSYS-1 Capability*
Core-Wide Thermal Hydraulics	Primary
Fission Gas Behavior	Primary
In- and Ex-Pin Fuel and Clad Motion	Primary
Sodium Boiling	Primary
Primary/Intermediate System Heat Transport	Primary
Structural Response	Primary
Inherent Reactivity Feedback	Primary
Passive Heat Removal	Primary
Control System Response	Primary
System-wide Power and Flow Transient Analyses	Primary
Source Term	Supporting: Determines timing, magnitude, and location of fuel failure.

*Primary capability indicates results are produced directly by SAS4A/SASSYS-1, while supporting indicates SAS4A/SASSYS-1 results are utilized in subsequent calculations by a separate tool.

1.3 Phase 1 Activities

This section provides a brief overview of the activities completed in Phase 1 of this effort. These activities fall within two categories: preliminary planning and development of the SQA program (Section 1.3.1) and completion of technical activities supporting SQA (Section 1.3.2).

1.3.1 Preliminary Development of SQA Framework

A key activity during Phase 1 was the initial planning and development of an SQA program that could broadly satisfy the requirements specified in NQA-1-2008/2009 [7, 8], DOE Order 414.D [9], and DOE Guide 414.1-4 [10]. This activity produced a simplified document hierarchy (Figure 1.2) and the associated configuration management (via Subversion[1]), testing, and ticket workflow (via Trac[2]) systems required to fulfill the relevant SQA requirements.

[1] https://subversion.apache.org

[2] https://trac.edgewall.org

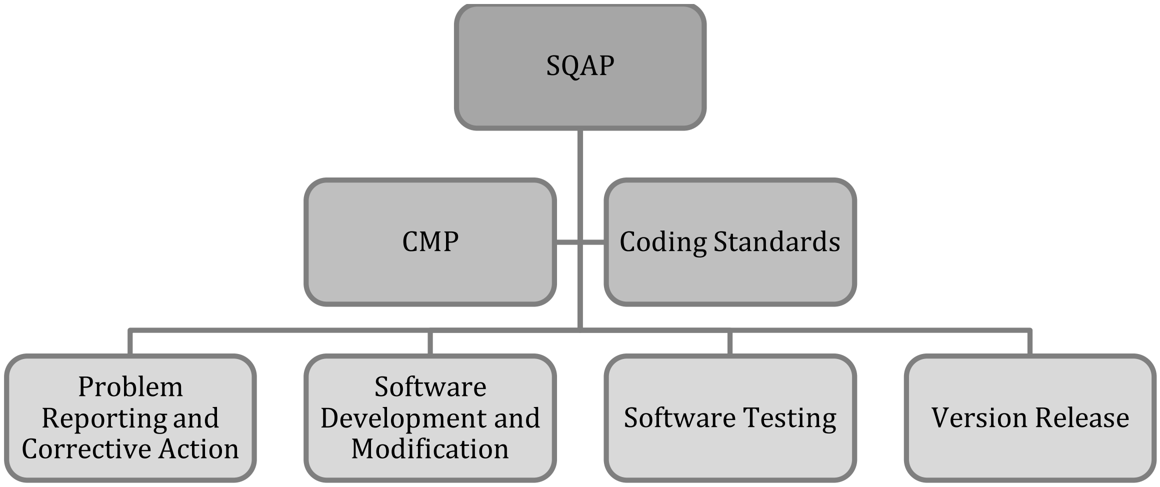

Figure 1.2: Graphical Representation of SQA Program Hierarchy

The SQA Program hierarchy consists of the following key documents:

- **Software Quality Assurance Plan (SQAP):** Acts as an entry point to the SQA Program and directs developers, managers, and SQA coordinators to the appropriate sublevel document. Provides an overview of all Program activities and requirements.
- **Configuration Management Plan (CMP):** A second-tier document. Describes configuration management (CM), the process of identifying, managing, and controlling the status and revision of software items. These activities are inherent in all procedures.
- **Coding Standards:** A second-tier document. Contains requirements for programming practices and conventions. Identifies relevant standards. Inherent to all SQA activities.
- **Procedures:** Third-tier documents. The following procedures are used in the SAS4A/SASSYS-1 SQA Program:
    - **Problem Reporting and Corrective Actions:** Prescribes steps for identifying, reporting, and correcting problems.
    - **Software Development and Modification:** Prescribes steps for the design and implementation of new features or models.
    - **Software Testing:** Prescribes steps for evaluating whether software adequately performs all intended functions.
    - **Version Release:** Prescribes steps for the formal release of software and delivery of products.

1.3.2 Technical Activities

In addition to preliminary development of SQA Program documentation during Phase 1, several quality-enhancing technical activities were completed. A brief summary of these activities is provided below.

- Addition of six test cases to the approved V&V test suite. These test cases address previous gaps in the suite, which were primarily in measured control signals.
- Development of automated testing via a Buildbot server. This automated functionality tests code repository functionality and integrity by performing a series of checkout, build, and simulation activities which are used to report any errors in the repository.
- Development of an interactive testing algorithm that facilitates development and maintenance activities. Primarily used as a developer tool, the algorithm executes a series of user-defined cases for various executables and identifies any errors or discrepancies in the output.
- Successful build and testing of the source code with an alternative compiler (NAG). In this process, several areas of the source code were improved by the addition of more robust arithmetic error checks, removal of nonstandard functions, and correction of errant type definitions.

1.4 Report Structure

The remaining sections of this report are structured as follows. Section 2 provides details on the implementation of the SAS4A/SASSYS-1 SQA Program as part of Phase 2. Topics covered in Section 2 include adoption of Program procedures as part of a trial application period and development of regular SQA surveillance schedules that will be in effect upon full Program implementation at the conclusion of FY17. Completion of a management-initiated internal assessment and revision of the plans and procedures as per findings of the trial application and assessment are also described in this section.

Highlights of quality-enhancing technical activities completed during Phase 2 are provided in Section 3. These technical activities include, but are not limited to, enhancements to qualification testing and code documentation. Creation of new validation problems, unit testing capabilities, and more expansive regression testing were the primary focus of Phase 2 technical activities.

Lastly, Section 4 highlights key findings of Phase 2, gaps remaining in the SAS4A/SASSYS-1 SQA Program, and activities that, if supported, would assist with reduction of advanced reactor licensing barriers as they pertain to development of codes and models acceptable for use in a licensing context.

2 Phase 2 SQA Program Implementation Strategy

The primary focus of Phase 2 was the finalization and formal implementation of the provisional SAS4A/SASSYS-1 SQA Program developed in Phase 1. This process, shown in Figure 2.1, involved a trial application period of the provisional Program, additional review and refinement of the plans and procedures that formulate the Program structure, a management-initiated internal assessment of the Program, revisions of the Program as per the assessment findings, and formal implementation of the Program. Details on each step of this process and the activities required to support each are described in additional detail below.

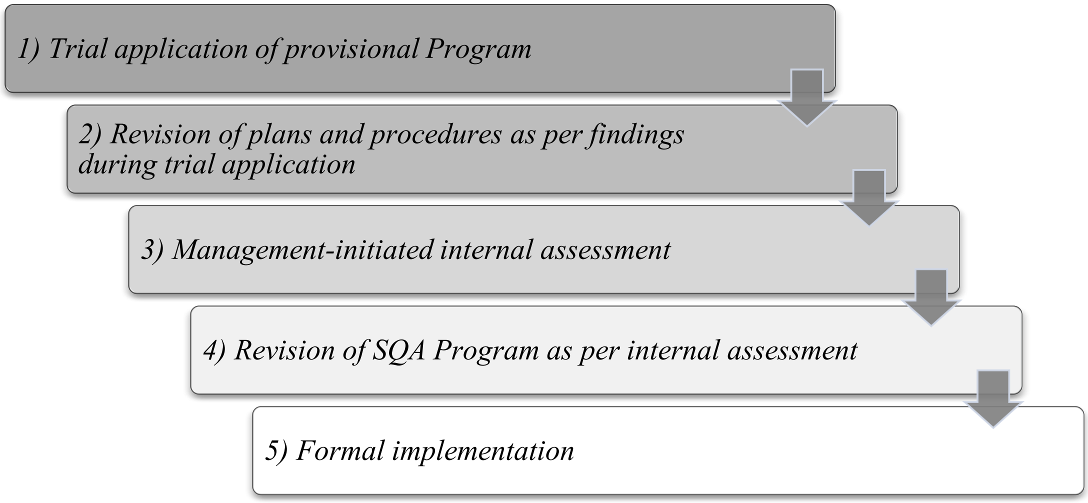

Figure 2.1: High-level Overview of SAS4A/SASSYS-1 SQA Program Implementation

1. *Trial Application and Procedure Adoption*

The provisional SQA Program underwent an eight-month trial application period in which a selected subset of developers, the Code Manager, and SQA Coordinator exercised the plans and procedures developed in Phase 1. During this period, the Trac ticket system, which was configured to reflect procedure requirements during Phase 1 [3], was utilized for gradual adoption of Program procedures. Utilization of each procedure was not scheduled, but instead adoption of each procedure occurred on an as-needed basis. That is, upon the onset of the trial application period, as development needs or problems with the code were identified, a ticket of appropriate type (e.g. Task, Error Report, Development, or Release) was created. Resolution of the ticket proceeded in accordance with the appropriate procedure: Task and Error Report tickets adhered to the *Problem Reporting and Corrective Action* procedure; Development tickets adhered to the *Software Development and Modification* and *Software Testing* procedures; and Release tickets followed the *Version Release* procedure.

During the trial application period, all ticket types capable of triggering entry into Program procedures have been generated and the relevant procedure has been exercised. With the exception of *Software Testing*, all procedures have been utilized multiple times throughout the trial application period, allowing for a comprehensive exploration of the benefits and limitations of Program procedures. Findings on usability, clarity, and consistency developed during the trial application were used to direct the documentation revisions completed in Step 2.

2. *Revision of Documentation as per Trial Application Findings*

As indicated above, the findings generated during the trial application in Step 1 were used to guide revisions to the SQA plans and procedures. While all plans and procedures underwent minor refinement in preparation for Step 3, the trial application resulted in identification of the following needs:

- Revision of the *Problem Reporting and Corrective Action* procedure to accommodate the processes necessary for changes to configuration items that exclude source code (e.g. the Code Manual, makefiles, etc.). The workflow associated with this procedure was broadened such that *minor* development tasks can be accomplished via usage of this procedure.
- Development of a series of review checklists to support the various review processes required as part of all procedures. These checklists provide reviewers with an abbreviated listing of key items or activities that should be included in a technical or QA review such that review consistency can be maintained. These checklists reference activities such as completion of development of activities in unique development branch spawned from an appropriate release branch and completion of sufficient documentation regarding development and testing.
- Development of a series of templates that support SQA documentation. Templates for the Software Requirements Specification (SRS), Software Design Description (SDD), and Software Test Plan (STP), all of which are required as per the *Software Development and Modification* procedure, were developed in order to enable consistency among developers.
- Minor modification of the SAS4A/SASSYS-1 SVN repository structure to accommodate storage of documentation and test problems developed as part of procedures. Program procedures require the creation and review of SRSs, SDDs, STPs, test problems, and reference solutions. As configuration items, these documents and inputs/outputs are subject to the configuration management and version control activities enabled by the SVN repository.

In addition to the documentation development activities described above, training on the SQA Program plans, procedures, and key SQA concepts was provided to developers and reviewers that have access to the SAS4A/SASSYS-1 repository. Staff with access to the SAS4A/SASSYS-1 repository that have not completed the SQA training cannot continue development activities as per the requirements of the SQA Program. Training was completed subsequent to the document revisions described above, as it is anticipated that Program documentation will not change significantly beyond its current state.

3. *Management-initiated Assessment*

A management-initiated internal assessment was launched to identify any significant issues in Program plans, procedures, or work activities. Internal Argonne personnel that typically support an NQA-1 certified program were utilized for this effort. Because the Program had not been fully implemented at the time of the assessment, the assessment focused on establishment and communication of the Program management structure, documented management involvement, and degree to which requirements have been implemented via the SQAP and procedure set. Findings of the assessment included one strength (S), one issue (I), and four improvement opportunities (IO). The four improvement opportunities were related to records management and characterization of the Program interfaces with external resources. The assessment cited the provisional status (i.e. lack of formal document approval) as an issue and the training material and activities as a strength. These findings, and their resolution status, are documented in Table 2.1.

4. *Revision of SQA Program as per Assessment*

The SQA Program documentation and work activities have been revised as per the findings of the internal assessment completed in Step 3. The four IOs have been addressed by revising Program documentation to include the items identified in the assessment; specific details of the resolution activities can be found in Table 2.1. To address the issue regarding lack of Program documentation approval, plans and procedures were reviewed and approved by the Code Manager, Division QA Representative, and SQA Coordinator prior to Program implementation.

Table 2.1: Summary of Internal Assessment Findings and Resolution

Type	Description	Resolution
Issue	Plans and procedures need to be approved prior to Program implementation.	Plans and procedures have been reviewed and approved by the Code Manager, Division QA Representative, and SQA Coordinator (SQAC).
Strength	Training material is thorough and complete.	N/A
Improvement Opportunity	Consideration should be given to who fulfills the role of Document Records Coordinator (DRC).	SQA Program documentation has been updated to include a DRC.
	Consideration should be given to adding a records section to each procedure that identifies relevant records parameters.	A Records section has been added to each procedure.
	Consideration should be given to adding an organizational chart that captures Lab-level, Division-level, and DOE interfaces.	An updated organizational chart has been added to the SQAP.
	Consideration should be given to integration with Argonne systems.	The Argonne records-management system and issue tracking system are now being utilized to track Program records and assessment findings.

5. *Formal Implementation and Continued Surveillance and Maintenance*

Formal, full implementation of the SAS4A/SASSYS-1 SQA Program occurred subsequent to the conclusion of Phase 2. Program plans and procedures were reviewed and formally approved by the Code Manager, Division QA Representative, and SQA Coordinator following revision of Program documentation as per findings in Step 3. Subsequent to approval, which signifies full, formal implementation of the Program, requirements of the Program are being strictly enforced.

Subsequent to formal implementation, the SQA surveillance schedules, which were developed during Phase 1 as an inherent component of Program documentation, will be enforced.

Surveillance activities include: annual reviews of Program documentation to ensure compliance with standards and requirements currently endorsed by the regulator; annual audits of SAS4A/SASSYS-1 SQA work activities to ensure compliance with the Program; annual review of the SQA Program to ensure alignment with Programmatic objectives; and annual configuration management audits.

Beyond annual surveillance schedules, continued maintenance of the Program requires regular code modifications to address bug fixes or implement new code features; development of SRS, SDD, STP, and other supporting documentation; requirements, design, technical, and QA reviews of tickets; and maintenance of an IT infrastructure (e.g. host servers, support tool software upgrades, etc.)

3 Technical Activities Completed in Phase 2

Throughout Phase 2, several quality enhancing technical activities that align with the recommendations in [5] were completed. The majority of these activities supported improved qualification testing, with particular focus on expansion of regression and unit testing capabilities and code validation. Improvement and modernization of code documentation was also initiated during Phase 2 with a major restructuring of the Code Manual that will continue.

Many of these activities, and primarily those related to testing, are expected to occur throughout the lifetime of the SAS4A/SASSYS-1 code. There is an initial, large-scale need for significant development of acceptance tests (V&V, regression, unit, etc.) that address the full scope of existing features in the code, as long-term maintenance of test problems has not historically been a priority due to resource limitations. Once a robust and comprehensive test suite has been developed for existing code models and features, ongoing testing activities can occur at a reduced resource level, as development of new tests would shift focus to new code development efforts only.

Currently, coverage of the V&V Test Suite is considered to be fairly comprehensive, with the majority of frequently used modules and features being tested[3]. Regression testing coverage, which is discussed in some detail below, is considered to need moderate improvement. Unit testing, a particular challenge for monolithic codes, requires significant additional development.

These testing improvements as well as additional technical activities completed during Phase 2 are described at a high-level below, with additional details being provided in the remainder of this section.

- Expansion of the verification and validation (V&V) Test Suite to include nodalization tests for key phenomena and models. New test problems examined the effects of varying the radial and axial fuel mesh discretization on agreement with an analytical solution.
- Recovery and recreation of historical validation test cases originally developed during the 1980s. These legacy inputs from SAS4A/SASSYS-1 v. 2.0 focus on selected oxide fuel

[3] The V&V Test Suite excludes validation of severe accident modules and is only focused on typical steady-state and transient kinetics and thermal-hydraulic phenomena.

experiment series in TREAT. Original validation reports generated in the early to mid 1980s used an early version of SAS4A[4]; the results are being regenerated with SAS4A/SASSYS-1 v. 5.2.

- Expansion of regression test coverage via addition of regression test problems. New test problems improve line-by-line code coverage for frequently-exercised modules.
- Initial development of point kinetics unit testing capability. SAS4A/SASSYS-1 program logic has been modified to perform a point kinetics calculation only.
- Conversion of the Code Manual [6] to a web-based format to improve usability and manageability. This activity enables the Code Manual to be updated more frequently as it simplifies the update process and interface.
- Improvement of the testing script used to support acceptance testing. The script executes a series of test cases and performs regression test comparisons to ensure continued code integrity.
- Release of version 5.2 partially under the provisional SQA Program. The latest release of SAS4A/SASSYS-1 is the first version of the code to adopt modern SQA practices.

Nodalization Tests

The existing V&V Test Suite has been expanded to include 117 new pin mesh nodalization cases. The objective of this effort was to examine the dependence of the SAS4A/SASSYS-1 solution on axial and radial pin discretization for key steady state and transient phenomena. Computational solutions generated by SAS4A/SASSYS-1 were compared to analytical solutions generated for each new case. Test results are considered acceptable if the deviation from the analytical solution is within the bounds of the error for the original test case that utilized a standard mesh.

Eleven cases from the original V&V Test Suite were utilized for this study. Pin meshing examined a combination of three to nine radial fuel nodes and one to sixteen axial nodes, resulting in the addition of nine to fourteen new meshes per original test case. Phenomena and models examined in the nodalization study include:

- Base steady state test case with standard core geometry,
- Modification of upper and lower reflector geometry for steady state calculation,
- Increase in reactor power to new steady state solution,
- Variations on correlations used for fuel thermal conductivity,
- ANS decay heat standard,
- Doppler, axial fuel expansion, and sodium void reactivity feedback,
- Treatment of reactivity feedback on fuel versus coolant mesh,
- Friction pressure drop, and

[4] The SAS4A/SASSYS-1 code existed as two separate codes, SAS4A and SASSYS-1, prior to the late 1980s. Early validation of severe accident modules utilized the standalone version of SAS4A and its predecessor, SAS3D.

- Core reference elevation.

Of the 117 cases, only four cases did not pass validation acceptance testing. Two cases failed due to stated code limitations regarding radial nodalization, whereas the remaining two failed due to poor axial discretization in the fuel thermal conductivity case. It should be noted that it is important to include tests in the Test Suite that demonstrate and confirm the stated limitations of the code, such as mesh size.

Legacy Validation Cases

Because SAS3A and SAS4A were or were anticipated to be heavily utilized for licensing of the Fast Flux Test Facility (FFTF) and the Clinch River Breeder Reactor these versions of the code underwent extensive and well-documented validation in the 1970s and 1980s. While much of the supporting documentation is readily available, regeneration of the SAS4A data using the latest version of the code is more challenging. Periodic updates in legacy data storage/retention, code input structure, and code input format (i.e. physical cards versus digital input files), as well as significant funding reductions in the 1990s, have led to maintenance gaps in the legacy inputs.

During Phase 2, four legacy validation cases have been regenerated using the latest version (5.2) of SAS4A/SASSYS-1 and compared to the historical validation reports. These inputs were recovered as v. 2.0 and v. 3.0 input files, meaning some level of effort was required to generate a working input deck due to input structure updates. All tests represent oxide fuel tests in TREAT. A brief summary of the experiment and the status of the validation test case are provided below in Table 3.1.

Table 3.1: Status of SAS4A/SASSYS-1 Legacy Validation Cases

Experiment	Description	SAS4A/SASSYS-1 Status
L03	Transient-undercooling-induced overpower in flowing sodium loop for UK-style fuel at varying burnup and clad strength.	Working input deck produces acceptable agreement with reported validation data for thermal-hydraulic behavior and fuel movement.
L07	Transient-undercooling-induced overpower in flowing sodium loop for UK-style fuel at varying burnup and clad strength.	Working input deck produces good agreement with reported validation data for thermal-hydraulic behavior and fuel movement.
TS-1	Slow transient overpower in flowing sodium loop for full-length irradiated FFTF driver fuel at varying burnups.	Working input deck produces excellent agreement with reported validation data for thermal hydraulic behavior, fuel movement, pin pressures, and fuel void worth. Noted improvement in prediction of clad strain.
TS-2	Slow transient overpower in flowing sodium loop for full-length irradiated FFTF driver fuel at varying burnups.	Partially-working input deck produces good agreement with reported validation data. Source code error likely result of simulation failure.

Expansion of Regression Testing Coverage

In addition to creation of new validation test cases on pin mesh nodalization, fifteen new regression test cases were generated to increase the line coverage of test cases in the regression test suite. It should be noted that these new cases do not represent validation of SAS4A/SASSYS-1 models or features, but are instead used solely for regression testing to ensure that code changes do not have unintended consequences. The V&V Test Suite, which does serve for validation of key models, is also utilized for regression testing.

New regression test problems focused on enhancement of code coverage in the modules most frequently used for typical transient calculations, MAIN and PRIMAR-4. New test cases were created for the following models and features:

- All frequently used flow element and compressible volume types available in SAS4A/SASSYS-1, including annular flow elements, check valves, thick-walled pipes, and compressible volumes with no cover gas,
- Detailed and simplified RVACS models,
- Simplified intermediate heat exchanger model,
- Lead and NaK coolant,
- Stratified treatment of compressible volumes with multiple outlet plena, and
- Detailed control rod driveline expansion model.

Existing models in the regression test suite include a broad range of basic modeling capabilities for generic reactor characteristics, including:

- Simple steady state,
- Simple transients,
- Alternative treatment of material properties,
- Point kinetics and reactivity feedback,
- Heat rejection system thermal hydraulics, and
- Control system signals.

Test cases for unprotected loss of flow transients in ABTR, protected and unprotected transient overpower simulations in EBR-II, and several M-series TREAT experiments are also included in the regression test suite.

With the new test problems described above, Intel's Code Coverage tool was used to assess the improved percent coverage of the regression test suite. Prior to inclusion of the new test problems, overall coverage (considering all modules) of the test suite was 23%; inclusion of the new test problems increases overall test suite coverage to 36%. Improvements to coverage of the test suite with regard to the MAIN and PRIMAR-4 modules, which were the focus of this effort, are provided in Table 3.2.

Table 3.2: Improvements to Test Suite Coverage

Module	Initial Coverage	Current Coverage
MAIN	41%	65%
PRIMAR-4	43%	55%
Overall	23%	36%

Details on test suite coverage per module are provided in Table 3.3. Shading in this table indicates ranges of basic block coverage, where a code block is considered to be a group of related lines of code (e.g. loops, if statements, etc.): red cells indicate block coverage of 0-25%; orange cells indicate block coverage of 26-50%; yellow cells indicate block coverage of 51-75%; and green cells indicate 76-100% block coverage. Modules with the lowest coverage per block include the balance-of-plant (BOP), DEFORM-4, and PLUTO2. Modules with the highest coverage include MAIN and the severe accident modules DEFORM-5 and PINACLE.

Table 3.3: Fractional Block Coverage of Test Suite Per Module

Module	Description	Block
BOIL	Two-phase coolant thermal hydraulics	0.35
BOP	Balance-of-plant systems and components	0.00
CNTL	Reactor and plant control systems	0.33
DATA	Data management	0.39
DEFORM-4	Oxide fuel/cladding mechanics	0.10
DEFORM-5	Metallic fuel/cladding mechanics	0.76
FPIN2	Pre-cladding-failure fuel relocation	0.34
LEVITATE	Post-cladding-failure fuel relocation	0.44
MAIN	Main program, logic path control, etc.	0.65
PLUTO2	Post-cladding-failure fuel/coolant interaction	0.18
PRIMAR-4	Coolant loops thermal hydraulics	0.55
PINACLE	Molten fuel relocation	0.68
TSCL	Coolant thermal hydraulics	0.38

While overall coverage of the test suite may appear low, it is important to recognize that the severe accident modules are quite large relative to the thermal hydraulic and kinetics modules and subroutines responsible for typical transient calculations. Hence, uncovered severe accident modules tend to bias overall code coverage; the balance-of-plant model also contributes to this bias. Closure of gaps in regression testing coverage should occur on a prioritized basis, where gaps in modules and features used more frequently in a wide range of designs should be addressed first. Engaging industry and other users to develop a prioritized list of analyses and reactor features would help address this issue.

Point Kinetics Driver for Unit Testing

Unit testing, a key element of acceptance testing, is difficult to support in monolithic codes such as SAS4A/SASSYS-1 due to the strong integration of modules and dependencies on shared data structures. During Phase 2, preliminary development of a unit testing capability for the point kinetics and decay heat models was completed by modifying SAS4A/SASSYS-1 program logic to prevent invocation of other SAS4A/SASSYS-1 modules. Currently, the point kinetics or point kinetics and decay heat models may be tested using the modified source code and a significantly simplified input file that does not require core or heat transport system geometry, material, or reactivity feedback input.

Code Manual Conversion

Currently, the SAS4A/SASSYS-1 Code Manual [6], which serves as requirements and design documentation for existing models and features, exists as sixteen separate Word documents totaling over 2,000 pages. Hosting Word documents in a repository poses certain challenges, such as storage of large files (incremental differences cannot be tracked) and inability to track changes unless Word-specific review feature are utilized. Backwards compatibility with older versions of Word for unique document features also presents an issue. Therefore, an effort has been initiated to migrate the Code Manual into a web-based format that requires less effort to maintain and update. Web-based hosting of the Code Manual also improves usability and navigability of the document, helping to address users' feedback regarding challenges learning the monolithic code. Conversion of the Code Manual in its entirety to restructured text (RST, a plain text markup syntax intended to support creation of technical documentation via web interfaces) has been completed. At this point, conversion of the Code Manual must be reviewed to ensure consistency with the original documentation and a web interface for the RST must be constructed.

Improved Testing Algorithm

During Phase 1, automated regression testing via Buildbot was preliminarily configured [3]. The test script utilized by Buildbot, which will automatically run a series of test cases and provide reports on acceptance, has been enhanced to provide developers with more control over what types (e.g. binary data, log files, standard output, etc.) of acceptance tests are performed, the comparator tool used (e.g. custom comparison that seeks specific information or a standard comparison of all data), and what cases are used as a reference solution. The test script also provides additional dynamic information on the results of acceptance testing for each case during execution of a set of cases.

Release of Version 5.2

Version 5.2 of SAS4A/SASSYS-1 was completed in March 2017 and released to users in May 2017. The latest release represents the first version of the code to undergo modern SQA practices. Development of version 5.2 began prior to initiation of the SAS4A/SASSYS-1 SQA Program trial application period, therefore a small number of code revisions were not subject to the SQA Program. However, a large number of development tasks, as well as the release process itself, underwent SQA review, all of which provided a thorough exercise of the provisional SQA plan and procedures.

4 Path Forward

Throughout this multi-year RTDP-sponsored effort, a provisional SQA framework was developed and tested for the SAS4A/SASSYS-1 safety analysis code. During its trial application period, the provisional SAS4A/SASSYS-1 SQA Program, which targets both NQA-1 and DOE SQA requirements, resulted in marked and traceable improvements in the code development process. Numerous bugs have already been reported and addressed and new development features are accompanied by requirements specifications, design descriptions, and appropriate testing documentation as per modern SQA practices, all of which are accomplished via consistent and systematic processes.

Given the successful trial application period, positive findings of the management-initiated assessment, and formal implementation of the Program, the SAS4A/SASSYS-1 SQA Program is at a sufficiently mature development state to enter into continuous production use and application at a level of about one FTE. Until there is a need identified to more closely align with a specific standard or requirement, the Program plans, procedures, testing methodology, and configuration management strategy do not need additional development. However, development of the *Program* is distinct from the development of requirements specifications, design descriptions, and testing documentation that is still needed for existing code features to support a commercial-grade dedication process. This is anticipated to require a moderate to significant level of effort.

Table 4.1: Identified Needs in the SAS4A/SASSYS-1 SQA Program

Gap	Importance	Lead Time	Comment
Long-term sustainment of SQA Program	High	Ongoing	Moderate resources are required to provide long-term support for the activities required by the SQA Program.
Engagement with NRC	High	Ongoing	Supports NRC's Near-Term Implementation Action Plans [11].
Engagement with industry	High	Short	Interaction with industry members on the suitability and completeness of the SQA Program to support future commercial-grade dedication (CGD) efforts and to help prioritize SQA needs.
Support for commercial-grade dedication	Medium	Ongoing	CGD by an industry-based code user will require direct support from developers. Future workload can potentially be reduced by completing early documentation development [3] for prioritized models.
Establishment of NQA-1 program	Low	Medium	In addition to quality enhancement, a certified NQA-1 SQA Program can be leveraged to support licensing activities.

In light of the effort required to support the activities that are required (e.g. technical reviews, documentation preparation, QA surveillance, etc.), the most significant challenge to the SAS4A/SASSYS-1 SQA Program is sustainability. While the SQA Program was developed to minimally affect the pace of the R&D workflow, all elements associated with SQA practices, such as bug fixes, code reviews, documentation generation, and SQA Program maintenance, do require resources to sustain. Resource demand during the early stage of implementation will be somewhat elevated as developers and reviewers learn and apply the practices required to comply with formal SQA processes. Current experience indicates that one-time training is not sufficient for developers to obtain expertise in the required skills and procedures. The SAS4A/SASSYS-1 SQA Program is entering this early-implementation stage as developers and reviewers have only recently been trained and are gradually developing more familiarity with and expertise in the SQA Program. Long-term resource demand for a well-established and mature team of developers will be reduced compared to the initial implementation period.

The obstacles described above do not address the additional need to support interaction with industry members and regulators regarding the suitability of the SQA Program. Table 4.1 provides a high-level overview of the activities that remain to be resolved at the conclusion of Phase 2 of this RTDP-sponsored effort.

Interaction with the NRC regarding acceptability of the SAS4A/SASSYS-1 SQA Program is considered a high priority task as it is directly related to the NRC's Non-LWR Near-Term Implementation Actions Plans (IAPs) [11], and in particular Strategy 2 on identification of suitable codes and methods for SFR analyses. Early engagement with the NRC on the pedigree of SAS4A/SASSYS-1 with regard to both SQA and V&V[5] will help expedite the advanced reactor licensing process. Currently, the NRC has begun preliminary discussions with Argonne regarding the capabilities of SAS4A/SASSYS-1, although the effectiveness of this activity is limited due to the lack of a formal arrangement. The DOE, who can authorize the operation of a limited set of reactor facilities, should also be approached regarding acceptability of the SAS4A/SASSYS-1 SQA Program. The findings of the DOE-NE Advanced Demonstration and Test Reactor Options Study [12] indicate that an SFR is the optimal candidate for test reactor construction, meaning there is a potential near-term need for systems-level SFR safety analyses where SAS4A/SASSYS-1 is the ideal tool for this application.

Beyond interactions with the regulator, engagement with industry members is needed to identify any potential gaps in the SQA Program, as it is ultimately the responsibility of the license applicant to perform commercial-grade dedication (CGD) of the software. During the CGD process, the quality of the SQA framework will be evaluated, as will the capabilities of the software itself. In this case, early engagement with vendors developing mature SFR designs will help reduce potential licensing burdens if deficiencies in the SQA Program are addressed in the near term.

During the CGD process, vendors and designers will require significant support from SAS4A/SASSYS-1 developers to complete the dedication activity. The CGD process typically requires comprehensive documentation of requirements specifications and critical characteristics for those models and features relevant to the safety analyses in question. Although SAS4A/SASSYS-1 has a comprehensive Code Manual, the code does not include the SQA documentation (e.g. requirements specifications, design descriptions, and test plans) now required by modern SQA practices. This documentation will need to be developed to some degree. Much

[5] Typically license applicants are responsible for validation of a specific model reflecting their design. However, it is expected that the SAS4A/SASSYS-1 code can achieve regulatory acceptance (similar to the DOE's Safety Software Quality Assurance – Central Registry toolbox codes) for use with conventional advanced reactor designs. Novel features or plants (e.g. heat-pipe designs) will require a validation and dedication process that must be completed by the applicant.

information can be gathered from the Code Manual, but requirements documentation is lacking and the design information that is available in the Code Manual is not sufficient to meet modern CGD requirements. Ongoing support for this activity will be needed as applicants enter the licensing process.

The final Program need identified in Table 4.1 is related to establishment of an NQA-1 certified program. Maintaining an NQA-1 program for SAS4A/SASSYS-1 would significantly increase the attractiveness of the code as a licensing tool. However, NQA-1 certification may not be necessary if a commercial-grade dedication process is completed by an applicant. It is expected that establishing an NQA-1 certified program would require significant lead time and resources. More importantly, an NQA-1 certified program would encounter the same sustainability issues the SAS4A/SASSYS-1 SQA Program is currently facing, as regular audits, assessments, and surveillance are also required to maintain the NQA-1 certification.

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